The effect of water hammer on a confined air pocket towards flow energy storage system
Mohsen Besharat, Reza Tarinejad and Helena M. Ramos

ABSTRACT
This research studies the behavior of a fully confined air pocket under the effect of water pulses induced by a water hammer phenomenon using several experimental tests in a pressurized transient condition. A compressed air vessel (CAV) has been tested under transient conditions to show its ability to absorb the pressure surges and to demonstrate the energy storage capability of the air pocket. Proper dimensionless parameters are introduced and the relationship between governing factors is analyzed. Smaller sizes of air pocket lead to higher pressures, and there exists a critical size associated with the higher pressure value depending on the flow velocity.

Key words | air pocket, compressed air vessel, flow energy storage, water hammer

NOMENCLATURE

\begin{align*}
H_{CAV} & \quad \text{initial head of air pocket inside CAV} \\
\bar{H}_{CAV} & \quad \text{peak head of air pocket} \\
H_{T1} & \quad \text{initial head of HT1} \\
H_p & \quad \text{initial head of pipe} \\
\bar{H}_p & \quad \text{peak head of pipe} \\
H_s & \quad \text{stored head inside the air pocket as pressure} \\
p & \quad \text{initial pressure of the air pocket} \\
p_{CAV} & \quad \text{pressure after transient action in the air pocket} \\
(p_{CAV})_{\text{max}} & \quad \text{maximum pressure of the air pocket} \\
V & \quad \text{average velocity} \\
D & \quad \text{pipe diameter} \\
v & \quad \text{kinematic viscosity of fluid} \\
\circ & \quad \text{initial value} \\
\text{BV} & \quad \text{ball valve} \\
\text{MV} & \quad \text{manual valve} \\
\text{CV} & \quad \text{check valve} \\
\text{CAV} & \quad \text{compressed air vessel} \\
\text{VFR} & \quad \text{volume fraction ratio} \\
\text{WH} & \quad \text{water hammer} \\
\text{Re} & \quad \text{Reynolds number}
\end{align*}

INTRODUCTION

Entrapped air within a water flow is of great importance since the maximum pressure that can be attained is much higher than a full-filled water flow due to the high compressibility of air. In addition, the entrapped air is capable of causing changes in the turbulence pattern during the pressurization phase that alters the shear stress at the wall. Any mixture of air and water changes the bulk properties of the fluid, such as the flow density and the elasticity, due to the pressurization of the air pocket (Lauchlan et al. 2005). Many researchers have studied the effect of entrapped air...
in pressurized systems to investigate its various effects, studying aspects such as different initial pressures and sizes of the air pocket, surrounding conditions and the length of the water column (Martin 1976; Cabrera et al. 1992; Martin 1996; Lee & Martin 1999; Zhou et al. 2002; Lee 2005; De Martino et al. 2008; Martins et al. 2009; Martins 2013). Martins (2013) studied the effect of entrapped air in pressurized vertical and inclined experimental pipe systems and found that the peak pressure can be much higher in the air-water condition than in the water-only condition. The author tried to define the effect of the change in initial pressure of the air pocket on the maximum pressure of the air pocket in rapid void pressurization tests and concluded the highest pressure was attained when the initial pressure within the air pocket was the atmospheric pressure. Accordingly, the maximum pressure increases until a peak value and then decreases as the void fraction increases gradually (Martins 2013).

The behavior of air pockets in pressurized systems under transient flow conditions is also very important due to the unpredictability of behavior and the complexity of analysis. Air volumes are also able to absorb and control high pressures induced by transient events. Various transient control devices can be used in pressurized systems, e.g., surge tanks, air chambers (vessels) and special relief valves. For that purpose in some cases, air vessels are more preferable because they can work under a wider range of pressure, they can be installed in diverse possible locations, they have small volumes and then they are more economic. Therefore, it is easy to apply them and their functionality is better (Chaudhry et al. 1985). The main role of an air vessel is to maintain the maximum and minimum pressures within the design limit of each system. In an air vessel there is a compressed air pocket above the water surface (Chaudhry et al. 1985). In this case, the pressure and the water level variation in the air vessel can affect the safety and efficiency of the system operation. Disclosing various aspects of an air pocket in a confined compressed vessel may increase knowledge regarding its behavior and yield easier and more reliable utilization for different purposes. Nowadays, the water hammer (WH) issue has become more important because of increasing concerns on the conveying capacity and system complexity of pressurized systems. Much research can be pointed out in design, stability and operation of air vessels. First studies of air vessels supposed a rigid water column, showing that the rigid column assumption is reliable if the maximum and minimum oscillations of pressure are less than half of the maximum pressure surge induced by instantaneous closure of a valve (De Martino & Fontana 2012). Stephenson (2002) used the rigid column assumption for calculation of both air volume and vessel volume in case of a pump failure. Kim et al. (2015) presented a work to investigate the behavior of an air pocket inside an air vessel and its dependence on parameters such as polytropic exponent, discharge coefficient, wave speed and initial size of the air pocket. Yang et al. (1992) presented a study about the stability of large oscillations in closed surge chambers using the direct method of Liapunov considering the nonlinear terms. This work suggests that the critical area is a product of Svee’s law and a factor greater than unity.

In addition, an air pocket shows the ability for energy storage. There is a rising rate of researches in renewable energy sources (RES) because of emerging problems such as environmental impacts, scarcity and economic aspects related to the fossil sources. Although the RES are abundant, their availability over time is an obstacle to engage them effectively. Compressed air energy storage (CAES) systems which take advantage of storage vessels either above or underground are promising and low-cost tools with high energy capacity (Proczka et al. 2013). In this system the energy is stored as pressure within an air pocket which can be recovered by air pocket expansion. Zhang et al. (2015) presented a study on an advanced adiabatic compressed air energy storage (AA-CAES) system coupled with the air storage vessels. They studied four air vessels and showed that each vessel presents distinct characteristics of the charge and discharge process. Grazzini & Milazzo (2008) presented a study of a CAES system and showed a magnitude of heat recovery and resulting energy recovery efficiency of 72%.

Conventional CAES systems depend on fuel or other energy storage plants to store and recover the energy, unlike the solution herein proposed. Current work uses WH to convert the kinetic energy of flow known as ‘flow energy’ to potential energy. The mentioned potential energy is stored in a compressed air vessel (CAV) as compressed air for later use. The compressed air, in an action
similar to CAES systems, can be expanded in order to recover the stored energy. In fact, this research was intended to provide information concerning practical approaches for storing energy in the form of compressed air in a vessel. To address this, the WH phenomenon was analyzed experimentally, with two generations of an experimental apparatus. The proposed case is able to store high-pressure created by a pressure surge inside an air vessel, which can be used to drive a micro-hydro turbine or to elevate water as a ram pump. The proposed system can be used in liquid conveyance systems as a lateral system to take a portion of main flow for storing energy. The separated flow will be returned to the main conduit after a WH action.

There is still space for more research studying the air pocket behavior inside a CAV for pressure controlling and energy storage purposes. To study this issue a specific CAV was developed in an experimental facility at the Civil Engineering, Research, and Innovation for Sustainability (CERis) Center, a research center of Instituto Superior Técnico (IST), the engineering faculty of the University of Lisbon, Portugal. The authors tried to reveal the effect of WH caused by an instantaneous closure of a valve on the pressure variation of a CAV, for various sizes of air pockets and different flow velocities inside the pipe system. Proper analysis based on dimensionless parameters is presented and discussed.

EXPERIMENTAL MODEL

Brief description

The experimental model was developed by improving the previous system of Martins (2013) in the CERis Center. Two types of the experimental models, i.e., system 1 and system 2 are used in this study. Two hydro-pneumatic tanks (HT1 and HT2) were considered in the system as a means to provide initial pressure and water required for different tests. Each tank has the volume of 1 m³. A set of transparent PVC pipes with 8 m length, nominal diameter of 63 mm (DN63), and a nominal pressure of 16 bar (PN16) is used to conduct water from HT1 towards HT2. A hydro-pneumatic CAV is installed on the highest point of the pipe and three pressure transducers identified as PT1, PT2, and PT3 are installed along the pipe to measure the pressure. A high-speed camera (500 fps) is used to capture the air-water interface during each transient flow. A trigger provides the electrical means to activate all measuring equipment. The experimental pressure data are acquired using a pico-scope system. The trigger controls the actuation of valves and the start of recording by the camera allowing a perfect synchronization of data collection. Then, the starting times of the experimental tests and hydrodynamic simulations coincide. There are four ball valves (BVs), identified as BV1, BV2, BV3, and BV4 to create different transient flow conditions in different pipe sections.

System 1

System 1 is a direct experimental flow model that conducts water from HT1 to HT2, as presented in Figure 1. System 1 provides a suitable tool to investigate the behavior of air pockets in a CAV, under WH conditions. Tests are conducted to investigate the behavior of the pressure oscillation inside the CAV with diameter of 140 mm and height of 325 mm due to WH action induced by the closure of valve BV3. The flow from HT1 towards HT2 is created

![Figure 1](https://iwaponline.com/aqua/article-pdf/65/2/116/399093/jws0650116.pdf)
with all valves fully open. After a defined time interval, valve BV3 is instantly closed to induce a severe WH in the pipe system. Then, the variation of the pressure within the air pocket is measured. The valve opening time is 0.20 s during the WH tests. The effect of a WH event induced by the closure of valve BV3 on the peak pressure inside the CAV, considering several air pocket sizes, from a completely empty CAV to an almost-full CAV is very important to the flow energy storage ability. Tests are conducted for two different initial pressures of HT1, i.e., 15.3 and 20.4 m. A sample of pressure oscillation of the CAV during the WH test in system 1 is shown in Figure 2.

System 2

System 2 consists of a loop circuit (Figure 3), which has a pump with maximum nominal head of 28.2 m and nominal power of 4 kW. The CAV has a nominal diameter of 110 mm and a height of 630 mm. Three spring cone check valves (CVs) are installed in system 2, one instead of BV2 and
other ones in locations shown in Figure 3. Also, in order to control the flow condition in the pipe system, three manual valves (MVs) are deployed. Installing CV2 in the CAV entrance location creates a confined CAV with the only outflow circuit controlled by MV1. System 2 was used to test the effect of a WH on the behavior of an air pocket with different sizes and flow velocities. The WH was created by instant actuation of BV4 for each different flow velocity and size of the air pocket.

**DIMENSIONLESS PARAMETERS**

In order to investigate how different flow conditions (such as initial/peak pressure and air pocket size) affect the behavior of the system, some dimensionless parameters were defined and studied as Equations (1)–(4).

\[ \Delta H_{CAV,T1} = \frac{H_{CAV} - H_{CAV}}{H_{T1} - H_{CAV}} \]  

(1)

where \( H_{CAV} \) is the peak head of the air pocket, \( H_{T1} \) is the initial head of HT1, and \( H_{CAV} \) is the initial head of the air pocket. Equation (1) shows the net increase in the head of an air pocket when a WH event occurs. The effect of the size of the air pocket also was taken into account by defining the volume fraction ratio (VFR). The VFR accounts for the ratio of the volume of the air pocket to the volume of the CAV. When the CAV contains no water, the VFR equals 1.

\[ \text{VFR} = \frac{\forall_{AP}}{\forall_{CAV}} \]  

(2)

where \( \forall_{AP} \) is the volume of the air pocket, and \( \forall_{CAV} \) is the volume of the CAV. In addition, another dimensionless parameter was defined to illustrate the action of the air pocket by comparing its peak head \( (H_{CAV}) \) with the peak head of the pipe \( (H_p) \).

\[ \Delta H_{CAV,p} = \frac{H_{CAV} - H_{CAV}}{H_p - H_p} \]  

(3)

where \( H_p \) is the initial head of the pipe. Equation (3) gives interesting results in terms of pressure variation in both the pipe and the CAV. The air pocket was able to absorb the pressure surge induced by a WH event and to retain it as stored energy for later use. The energy storage inside the air pocket is a function of the initial pressure of HT1 and the size of the air pocket (indicated by VFR). Therefore, specific analyses were developed to study how these two parameters \( (H_{T1} \text{ and VFR}) \) affect the storage capacity of an air pocket. To do that, a new dimensionless parameter was considered to show the variation in the storage of pressure:

\[ \Delta H_{s,T1} = \frac{H_s - H_{T1}}{H_{T1}} \]  

(4)

where \( H_s \) is the energy storage (i.e., as pressure increasing) inside the air pocket. These dimensionless parameters were used to describe the behavior of an air pocket inside a CAV for two-phase flow conditions.

**RESULTS AND DISCUSSION**

**System 1**

The defined dimensionless parameters in the Equations (1)–(4) are analyzed, in order to demonstrate the influence of each parameter on the behavior of the air pocket. Equation (1) provides the ability to study how a change in the size of the air pocket can increase the pressure. In accordance with that relationship, Figure 4 shows that decreasing the size of the air pocket for both of the initial pressures of 15.3 and 20.4 m increases the peak pressure in the air pocket. A different behavior was detected for this dimensionless parameter than the case in the rapid void pressurization studies of other researchers. Zhou et al. (2014) and Martins (2013) showed that the peak pressure of an air pocket raised and then declined when the size of the air pocket was decreased. In this research, a continuous decreasing of the size of the air pocket induced a continuously increasing peak pressure. In addition, Besharat et al. (2014) introduced an efficient void volume, which corresponds to the highest pressure under a rapid pressurization. It was not possible to determine the same efficient volume in the WH tests due to the different behaviors of the air pockets.
Equation (3) introduced a parameter to compare the increase in pressure of the air pocket with the pressure of the pipe. Experimental measurements clearly showed that $\Delta H_{CAV,p}$ is not a function of the size of the air pocket; rather, it was constant for various VFRs except for those that were less than 0.20 (Figure 5). This indicated that small VFRs are not dependent on the initial pressure of the HTs.

During this research, the authors developed the concept of using the pressure surge as a means to compress air, thereby a way to store flow energy as compressed air within a CAV comparable to a CAES system. Based on the results shown in Figure 6, an appropriate volume for the air pocket can be selected to store the highest pressure and/or to be able to maintain the security of the system. To assess the ability of storing energy, the $\Delta H_{S,T1}$ characteristic parameter, defined in Equation (4) and depicted in Figure 6, allows better definition of the energy storage in different air pockets.

The maximum capability for storing energy corresponded to a low VFR when the VFR was less than 0.20. However, the air volume also demonstrated storage capabilities for VFRs exceeding 0.30. The minimum storage capacity occurred for VFRs from 0.20 to 0.30.

Photographs presented in Figure 7 declare that experimental tests had uniform increases in the level of the

![Figure 4](image1.png)

**Figure 4** | Variation of $\Delta H_{CAV,T1}$ against VFR.

![Figure 5](image2.png)

**Figure 5** | Variation of $\Delta H_{CAV,p}$ against VFR.
water column inside the CAV during the WH tests. The air-water interface remained constant even after several consecutive WH actions, as shown in Figure 7, a stable behavior of water surface with very low mixture of air and water that is very significant for energy storage purpose using compressed air action.

**System 2**

Figures 8 and 9 illustrate the variations of pressure characteristic parameter along a period of the WH process for VFR = 0 and VFRs in the range of 0 < VFR < 0.65, respectively, under different Reynolds (Re) numbers. Reynolds number is defined as $Re = \frac{V D}{\nu}$ where $V$ is the average velocity in the pipe, $D$ is the pipe diameter and $\nu$ is the kinematic viscosity. The characteristic parameter is defined as:

$$p^* = \frac{p_{CAV} - p_o}{p_o}$$  \hspace{1cm} (5)

where $p_o$ is the initial pressure of the air pocket and $p_{CAV}$ is the pressure after the transient action.

For VFR = 0, in the absence of the air and consequently its compressibility effect, pressure fluctuations are restricted and the damping occurs more or less after 0.2 s (Figure 8). However, this can be a dangerous case, especially at higher Reynolds number since the hydrostatic pressure of the water column within the CAV is high and the ability of the mass absorption from the pipeline is very low, and the probability
of a rupture in the pipeline seems to be high in this case. Beyond the VFR = 0, a regular manner of the CAV with respect to VFRs and the Reynolds numbers can be seen in Figure 9.

Figure 8 | Variation of pressure characteristic parameter within air pocket along the time for VFR = 0.

Hence, some conclusions can be addressed, as follows. (i) Increasing the value of VFR decreases the pressure fluctuations for each individual Reynolds number. This is due to higher interaction between the air and water column within the CAV in lower VFRs. (ii) For each individual VFR, the damping period is proportional to the Reynolds number, e.g., in the case of VFR = 0.0317, while the fluctuation dissipates after about 0.27 s for Re = 36,000, this dissipation occurs after about 0.9 s for Re = 115,000, indicating the significance of the WH phenomenon in higher Reynolds numbers. (iii) Due to the higher compressibility effect of the air at higher VFRs, the damping period of the pressure fluctuation increases with the VFR. From the perspective of the imposed normal stress and air vessel safety, longer damping periods can be preferred since the pressure variation and dissipation occur gradually.

Figure 9 demonstrates the variations of the pressure characteristic parameter along the time of WH for higher
VFRs (0.10 < VFR < 0.65) and different Reynolds numbers which demonstrates the effect of increase in the size of air pocket clearly.

Fluctuations of the pressure become smaller by increasing the VFR and decreasing the Reynolds number. This reduction for higher VFRs is due to the higher stu...
compressibility effect of the air, which allows higher amounts of flow mass absorption in the CAV. Pressure fluctuations for all Reynolds numbers become minimum in the case of high VFR in the tested VFR range.

Figure 11 shows the experimental data associated with the distribution of the maximum air pressure in the CAV, i.e., $(P_{CAV})_{\text{max}}$ with VFRs under different Reynolds numbers.

The attenuation of the Reynolds number role on the development of the maximum pressure can be noticed with the increasing of the VFR number, due to higher ability of the CAV in the mass absorption. On the other hand, a pressure jump is seen for the Reynolds numbers of 115,000, 132,000 and 155,000 in the case of $VFR = 0.0317$, due to the higher incoming flow mass demand and the lower air compressibility effect. This reveals that by increasing the Reynolds number, the compressibility effect of the CAV and consequently the VFR value should be increased for the hydraulic pipeline design point of view.

**CONCLUSIONS**

This research showed the ability of an air pocket in system 1 to store energy in the form of compressed air volume. Results also demonstrate how decreasing the VFR can affect the peak pressure in an air pocket. CAES systems with a very low VFR would be troublesome with respect to the effect of the size of the air pocket on the pressure increasing. An efficient VFR was analyzed and because of the interface behavior, the VFRs less than 0.20 would be preferable for use in storing energy in system 1. Likewise, the proposed characteristics parameters showed the ability of the experimental apparatus to store energy in a CAV by compression of different sizes of air pockets. The parameter $\Delta H_{CAV,p}$ demonstrated a quasi-linear relationship between the maximum pressure of the CAV and the pipe system. Small VFRs had different behavior that arose from their lower damping capability. Consequently, the pressure in the air pocket was closer to the pressure inside the pipe, and the maximum pressure in both was higher for small VFRs. Thus, it is possible to select an efficient VFR for converting kinetic energy to potential energy that can be stored in an air pocket. An efficient VFR must integrate high pressure storage with stable behavior of the air-water interface.

Accordingly, a laboratory study was carried out in system 2 in order to investigate the performance of an air vessel (CAV) in pressure control during a WH phenomenon. Experiments were performed over a wide range of VFRs and Reynolds numbers. It was revealed that the value of the VFR and the Reynolds number had a significant role in the pressure rising control during a WH event. In addition, increasing the VFR value (compressibility effect), allows a higher absorption of the flow mass during a WH event. Finally, the performance of a CAV in WH control depends on the VFR and flow velocity.
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